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Modeling of fiber pullout behaviors of stiff fiber reinforced cementitious composites

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Abstract. This paper presents numerical studies of stiff fiber pullout behaviors of fiber reinforced cementitious composites based on a progressive damage model. The ongoing debonding process is simulated. Interfacial stress distribution for different load levels is analyzed. A parametric study, including bond strength and the homogeneity index on the pullout behaviors is carried out. The numerical results indicate that the bond stress decreases gradually from loaded end to embedded end along fiber-cement interface. The debonding initially starts from loaded end and propagates to embedded end as load increasing. The embedded length and bond strength affect the load-loaded end displacement curves significantly. The numerical results have a general agreement with the experimental investigation.

Keywords: pullout behavior; fiber reinforced composites; debonding; damage; numerical simulation.

1. Introduction

Cement based matrix is brittle in nature but can be converted into a pseudo-ductile material effectively and economically with addition fibers. In corporation of fibers in cement based matrix has advantages in term of high fracture toughness, high strength, high impact and fatigue resistance (Li and Lim 1988, Zhang and Li. 2002, Ong, Basheerkhan and Paramasivam 1999, Li and Leung 1988, Li 2002, Yang *et al.* 2003, Ramadoss and Nagamani 2009, Ramadoss and Nagamani 2008, Ramadoss and Nagamani 2006). In practice, those properties make it a promising alternative for structures. The mechanism of strength and toughness increase from fibers is complicated. Generally, fibers can bridge the crack; absorb energy by fiber pullout, fiber fracture and plasticity. Especially when the rigid and brittle fibers, such as carbon and glass fibers are used, it is the fiber-matrix interface properties that play an important role in the fracture mechanism of composites.

The single fiber pullout test, introduced decades ago, is one representative method and has now become an important experimental technology in assessment the mechanical behavior of fiber composites. However, it is complicated task to determine the direct pullout behaviors of a single carbon or glass fiber because most fibers have small diameter and low strain capacity. It is different to obtain some details for the fiber pullout test, such as the distribution law of stresses along the interface.

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Many researchers have also attempted to develop sophisticated interface models to represent the behaviors of the interface during crack propagation. For example, the earliest known shear-lag models (Hutchinson and Jensen 1990, Freund 1992) and cohesive zone models based on atomic theory and fracture mechanics (Needleman 1987, Tvergaard 1990). Note that the shear-lag models for interpretation of experimental data relies on some simplified theoretical ideas, mostly based on the assumption of constant shear stress distributions along the fiber length, and provides an approximation of interfacial shear and normal stresses. Many works have been done in applying fracture mechanics to simulate the interfacial debonding process based on the newly developed cohesive zone models (Geubelle and Baylor, 1998, Schryer and Peffer 2000). These analyses focus on establishing a constitutive relation between tractions acting on the surface and the corresponding interfacial separation and can explain the experimental results well.

Although the aforementioned models of interface have been widely accepted, few of the existing models can take the heterogeneities of materials into account. Better understanding and modeling of the pullout behaviors can help not only analyze the performance of a composite for different interfacial conditions, but also optimize interface bond characteristics for improved performance of the composite. In this paper, a numerical code, RFPA^{2D} (Realistic Failure Process Analysis code), based on the theory of elastic-damage mechanic is used to investigate carbon fiber pullout behaviors. The FRPA^{2D} was originally developed by Tang (1997), based on FEM (Finite Element Method) and improved at Mechsoft, China. It can be used to simulate the deformation, fracture initiation and fracture propagation in heterogeneous materials.

2. Numerical simulation model

As the details of the RFPA^{2D} code that is adopted in this study have been fully documented by Tang (1997) and Tang *et al.* (2008), the principles of the computer model are only briefly outlined here.

In RFPA^{2D} model, materials are assumed to be composed of many elements with the same size, and the mechanical properties of these elements are assumed to conform to a given Weibull distribution as defined in the following function

$$f(u) = \frac{m}{u_0}\left(\frac{u}{u_0}\right)^{m-1}\exp\left[-\left(\frac{u}{u_0}\right)^{m}\right] \tag{1}$$

where u is the parameter of the element (such as strength or elastic modulus); the scale parameter, u_0 is related to the average of the element parameter and the shape parameter, m, defines the shape of the distribution function. According to the definition, a larger m implies a more homogeneous material. We therefore call this parameter (m) the homogeneity index. In general, we assumed that the Young's modulus and strength (compression and tension) of elements that are used to simulate specimen conform to two individual distributions with the same homogeneity index. The elements are assumed to be isotropic and homogeneous.

At the beginning, the element is considered elastic, and its elastic properties can be defined by Young's modulus and Poisson's ratio. The stress-strain curve of an element is considered linear elastic until the given damage threshold is attained, and then is followed by softening. We choose the maximum tensile stress criterion and Mohr-Coulomb criterion respectively as the damage thresholds. In elastic damage mechanics, the elastic modulus of the element may degrade gradually as damage progresses. The elastic modulus of damaged material is defined as follows (Tang 1997).

$$E = (1-\omega)E_0 \tag{2}$$

where ω represents the damage variable, E and E_0 are elastic modul of the damaged and the undamaged material, respectively. Here the element as well as its damage is assumed isotropic and elastic, so the E and E_0 are all scalar.

The numerical approach to the fracture problem can be described as the following: our numerical simulation involves the calculation of the stresses acting on the elements and the mechanical property change of the damaged elements according to the constitutive laws and strength criterion described above. The value at which a particular element fails is random, but fixed at the start of the modeling process (that is, the disorder is quenched). The statistical distribution of the breakdown thresholds is a material property and is described by Eq. (1). Under a quasi-statically increasing external stretch the stress or strain of the elements are given by the solution of the FEM for mechanical equilibrium at each FEM node. If the stress of an element attains its prescribed breakdown strength, the element fails irreversibly. This is followed by additional relaxation steps, in which the new equilibrium positions are calculated. In the brittle regime these steps may lead to the failure of additional elements. The simulation of crack initiation and propagation in this investigation is just as the method used in the smeared crack model, the crack is smeared over the whole element, which has the advantage of leaving the mesh topology untouched (Pearce *et al.* 2000). No special singular element is adopted. Iterating the procedure leads to fracture propagation, where fractures are defined by groups and alignments of failed elements (Tang *et al.* 2008).

In this numerical model, the fiber reinforced cement matrix is assumed to be a three-phase composite composed of matrix, fiber and matrix–fiber interfaces, as shown in Fig. 1. The four-node isoparametric elements are used for the matrix, fiber and interface. The specimen consists of a fiber with various lengths and diameters (D) embedded partially in a concrete substrate (15 mm $\times$ 25 mm). The embedment length (L) was designed in multiples of the fiber diameter. The thickness of the interface is 0.02 mm and a single layer of 2-D four-node isoparametric element through the thickness of the interface is used.

The primary aim of this paper is to investigate the debonding behaviors. Thus, interfaces are assumed to obey the damage model mentioned above while the fiber and the matrix are linear elastic. The model is numerically simulated as a plane stress problem. Loading is applied through imposed lateral displacements on loaded end of the fiber with other three sides of the cement matrix restrained.

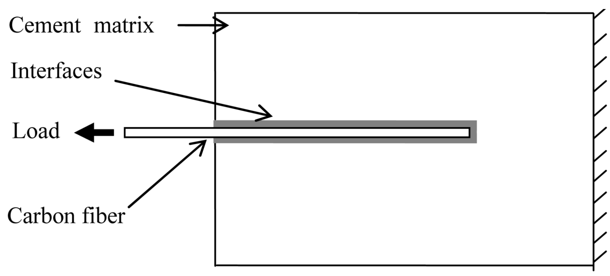


Fig. 1 The sketch of the fiber pullout model

3. Numerical results

3.1 Pullout process

According to experimental investigation by Amnon Katz and Victor C. Li (1995), the fiber, matrix and fiber/matrix interfacial properties used in the analysis are listed in Table 1. The homogeneity index (m) is 3, which is discussed in the following paragraph.

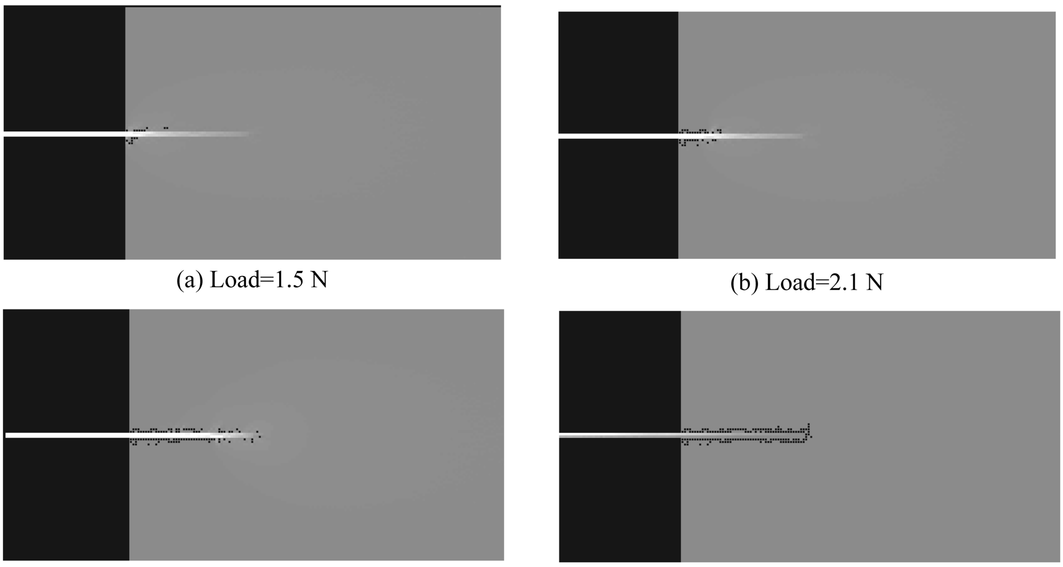
The typical pullout process is presented in Fig. 2. The fracture initiates at the loaded end in the bond zone and propagates to the embedded end with increasing load. Correspondently, the shear stresses along the embedded fiber length under different load levels are shown in Fig. 3. The numerical results indicate that there is a high stress concentration at the critical point where debonding reaches. The shear stress is not uniform along the embedded fiber length. For each load level, the shear stress always reaches it maximum value at the critical point, which may be the cause of the interfacial debonding. The shear stress decreases nonlinearly to zero from critical point to embedded end along the embedded fiber length. Fig. 3(c) indicates that the maximum pullout load occurs under partial interfacial debonding. And the complete debonding is represented by an almost constant shear stress distribution, as shown in Fig. 3(d).

Amnon Katz and Victor C. Li (1995) carried out an experimental investigation of carbon fibers

Table 1 Material parameters used in numerical model

Items	d_f (mm)	E_f (GPa)	E_m (GPa)	σ_f (MPa)	f_b (MPa)
Values	0.046	175	20	930	0.4

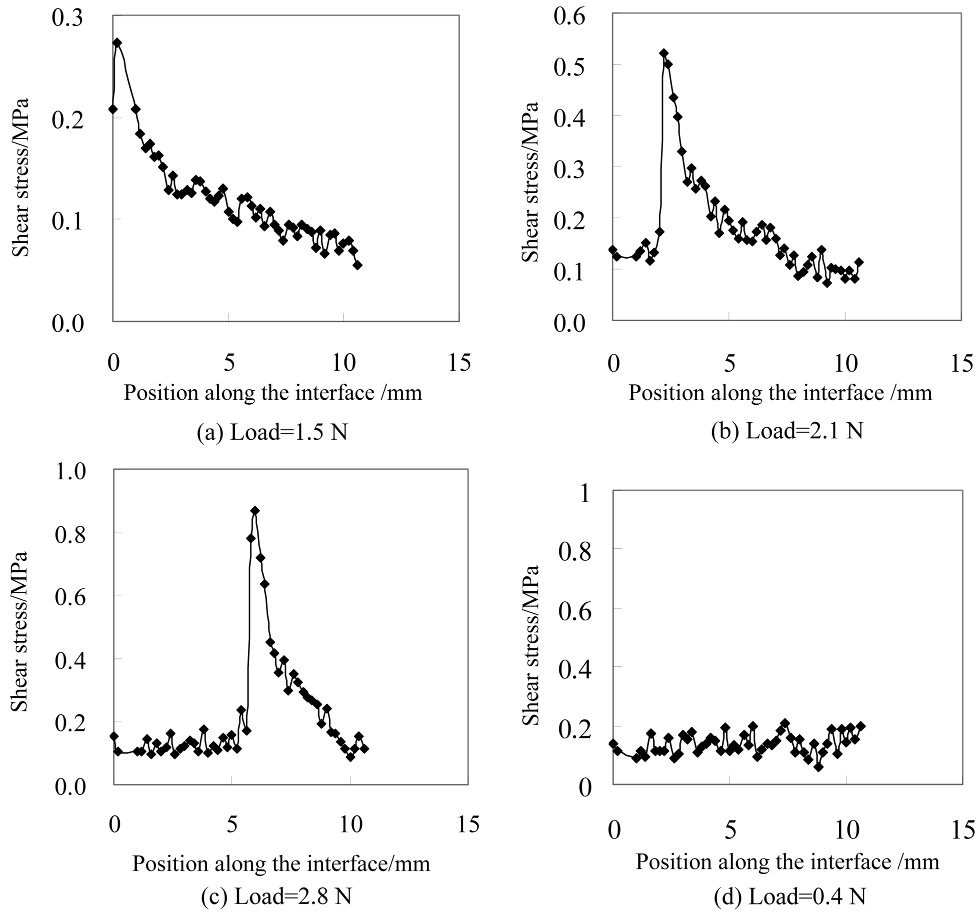
d_f, the diameter of carbon fiber; E_f, elastic modui for fiber; E_m, elastic modui for cement matrix; σ_f, tensile strength for fiber; f_b, cohesive strength for bond zone



(a) Load=1.5 N (b) Load=2.1 N

(c) Load=2.8 N (d) Load=0.4 N

Fig. 2 The numerical debonding process of fiber pullout



(a) Load=1.5 N

(b) Load=2.1 N

(c) Load=2.8 N

(d) Load=0.4 N

Fig. 3 Shear stress distribution along the interface for various load level during the debonding process

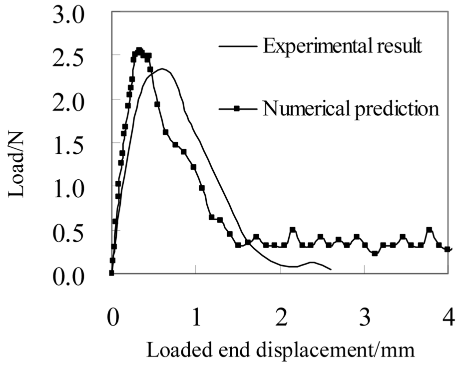


Fig. 4 Comparison between numerical prediction and experimental results on fiber pullout response

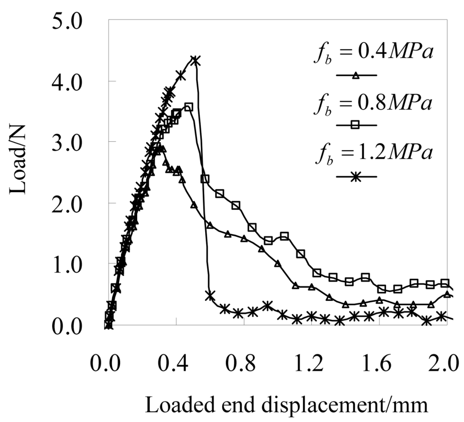


Fig. 5 Fiber pullout responses with various interface cohesive strength

pullout behaviors. The numerical and experimental load-loaded end displacement curves are compared in Fig. 4. Note that the numerical simulation is in agreement with the experimental results. The material parameters used in the experimental test are listed in Table 1.

3.2 Effect of interface cohesive strength (f_b) on pullout response

As an important micro material property, fiber/matrix bond parameter has been extensively investigated by researchers. In experimental investigation, the interface cohesive strength is readily affected by various factors, such as fiber surface, water cement ratio and so on. In this section, the influence of fiber/matrix interfacial cohesive strength on the pullout response will be studied using the above model. The fiber and matrix material parameters used in the analysis are the same as those listed in Table 1 except that the cohesive strength is treated as a variable parameter. According to experiment test by Amnon Kazt, the interface cohesive strength adopted for our numerical model ranges from 0.3 to 1.3 MPa. Typical numerical result of interface cohesive strength on pullout response is shown in Fig. 5. The peak load increases with increasing the interface cohesive strength when fiber embedded length and other parameters are kept the same.

3.3 Effect of the homogeneity index

As mentioned above, the mechanical properties of the elements in our models are assumed to conform to a given Weibull distribution to reflect heterogeneity of fiber-concrete bond. So, the homogeneity index, *m*, is one of significant factors affecting pullout behaviors. In order to study the influence of heterogeneity on the peak load, six different values of the homogeneity index, *m*=1, 2, 3, 4, 6, 8 are used for numerical models, while keeping other parameters constant. Numerical simulations show that the peak load is non-linearly related to the homogeneity index. Higher homogeneity index leads to increasing of peak load, as shown in Fig. 6.

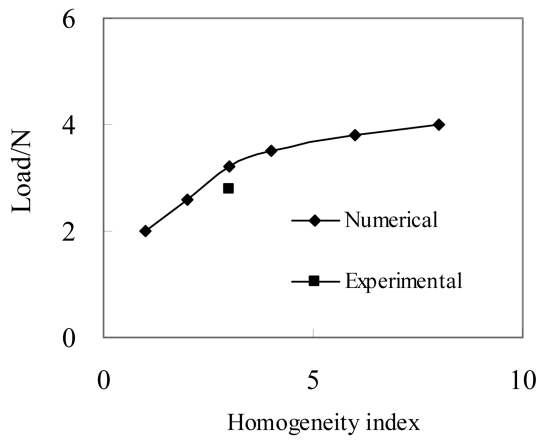


Fig. 6 Effect of homogeneity index m on peak load

4. Conclusions

Numerical studies of fiber pullout behaviors of fiber reinforced cementitious composites are performed based on a progressive damage model. The numerical results of shear stress distribution along the fiber indicate that the debonding process initially starts from the loaded end and propagates to the embedded end. The maximum pullout load occurs under partial interfacial debonding. The numerical simulation can adequately reproduce the ongoing process of debonding nucleation and propagation. The numerical results have a general agreement with test results.

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